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DOI
10.1016/j.marpolbul.2024.116966

Publication date
2024

Document Version
Final published version

Published in
Marine Pollution Bulletin

Marine Pollution Bulletin 208 (2024) 116966

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

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ARTICLE INFO

Keywords:
Hazardous cargo operations
Risk assessment
Seaport infrastructure
Port safety
Bayesian network
Causation factors

ABSTRACT

Seaport infrastructure requires considerable resources and time for a full recovery from accidents caused by hazardous cargo. Despite their severity, the risk to seaport infrastructure from hazardous cargo operations has been insufficiently explored. This study aims to fill that gap by examining the risks to seaport infrastructure from the complex effects of hazardous cargo operations. It draws on literature, incident reports, and expert consultations to identify comprehensive risk factors and their interconnections. The study employs expert judgments alongside logistic regression to develop Conditional Probability Tables (CPTs) and conducts a risk analysis using Bayesian networks (BN). Our findings indicate that, under typical operating conditions, fire and explosion, corrosion, and improper handling are the most significant contributors to seaport infrastructure risk with probabilities of 8.73 %, 5.88 %, and 5.61 % respectively. Inverse propagation indicates that the contribution of improper handling and corrosion is enhanced by 153 % and 96 % respectively towards the increased risk. A sensitivity analysis was carried out to pinpoint critical risk factors. Based on these insights, the study suggests practical measures like the use of tracking and monitoring systems along with third-party audits for effective handling, augmented and virtual reality for advanced training, and automation technology for reduced human roles to subside risks to seaport infrastructure and promote uninterrupted operations.

1. Introduction

The global economy relies heavily on maritime transportation, particularly the safe and efficient handling of hazardous cargo at seaports (Mazurek et al., 2022; Khan et al., 2023; Chen et al., 2020a). Despite the critical role of these operations, seaports face numerous risks (Hossain et al., 2019), including accidents, natural and environmental hazards, and operational disruptions (Wei et al., 2022; Bathgate et al., 2022), that can have far-reaching impacts on global supply chains (Rose et al., 2018). The complexity and potential for catastrophic outcomes underscore the urgent need for comprehensive risk assessments at these critical junctures (Kurth et al., 2020).

1.1. Accidents overview and port infrastructure risk

The risk that seaport hazardous cargo operations pose to the infrastructure is scarcely explored. Several studies concentrate on marine contaminations instigated by such accidents. For example, the impact of maritime accidents on the marine environment (Ceyhun, 2014), the marine pollution caused by petroleum and its recalcitrant compounds (Mahjoubi et al., 2018), oil spill pollution from global oil tankers (Chen et al., 2019), and the marine pollution caused by the container ship accidents (Wan et al., 2022). While many others assess the financial aspects of the losses, for instance, the impact of vessel-based maritime accidents on the economic conditions of Nigeria (Chinonyerem et al., 2017), investigations revealing that the collisions of tankers account for 81 % of the economic losses (Uğurlu et al., 2015), and ships with sinkings accidents, being away from ports and heavy weather conditions result in higher financial losses (Wang et al., 2021). There is a concentration on energy production and carriers in the literature, including the factors identification of oil spill accidents (Akyuz and Celik, 2018), and root cause determination for the explosion accidents of offshore gas storage and offloading facilities (Vinnem, 2018). Likewise, human factor determination in the hydrocarbon leakages (Almeida and Vinnem,

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https://doi.org/10.1016/j.marpolbul.2024.116966
Received 9 June 2024; Received in revised form 21 August 2024; Accepted 8 September 2024
Available online 13 September 2024

2020), comprehensive investigation of the past maritime accidents involving oil and its derivatives (Galieriková et al., 2021), and the overview of the fire and explosion accidents in the maritime transport (Baalisampang et al., 2018). The associated contamination features after incidents illustrates the scale and prominence of this domain in literature. Apart from this, several studies assess the effects of accidents on carriers with radioactive shipments, including risk assessment for catastrophic accidents of nuclear materials transport through Turkish straits (Bolat and Yongxing, 2013), and risk assessment and collision probability quantification for spent nuclear fuel maritime transportation (Christian and Kang, 2017). Likewise, analysis of accident risk and response system for the maritime transport of radioactive waste (Jin, 2018), and the frequency analysis for multi-factor induced accidents of spent fuel maritime transportation (Tao et al., 2022), along with the associated perilous consequences of such accidents. Apart from these discussed studies, a plethora of literature is concentrated on the transport of hazardous cargo and the associated calamitous consequences in the form of environmental and monetary losses (Chen et al., 2020a; Yu et al., 2021b).

Existing studies have often focused on general maritime safety and disaster resilience for hazardous cargo, including stowage planning in ships (Ambrosino and Sciomachen, 2021; Ambrosino and Sciomachen, 2015), behavior of different hazardous goods in hazardous cargo accidents (Galieriková et al., 2021), and the contributions of various causation factors towards maritime hazardous cargo accidents (Ma et al., 2022). However, this leaves a significant gap in our understanding of the specific risks associated with the handling of large volumes of hazardous cargo at seaports (Xie et al., 2021). This gap is particularly concerning given the disastrous incidents at Tianjin Port and the Port of Beirut, which highlight the severe consequences of inadequate risk management in this context. In this regard, the factors causing the Tianjin Port accident and the explosive substances have been investigated, without delving into the infrastructure risk (Huang and Zhang, 2015). Also, the role of human and organizational factors in the causation of the Tianjin Port accident was investigated, but the risk posed to seaport infrastructure was not considered (Zhou et al., 2018). Another study focused on the causation factor analysis for the hazardous cargo incident at Tianjin port and proposed a governance strategy, but it failed to cover the aspect of infrastructure risk (Hua et al., 2021). Likewise, a model was developed to assess the impact of information flow on accident causation and tested from the perspective of the Tianjin Port incident, however, the risk to the seaport infrastructure was not assessed (Wu and Huang, 2019). The post-disaster operational vulnerability assessment for the Tianjin port has also been conducted employing a novel approach without considering the infrastructure risk (Cao and Lam, 2019). Furthermore, the safety of ports and the perils posed to the food and economy of the countries as a result of devastating accidents have also been discussed (Mehan and Jansen, 2020). Investigations have been conducted on the legal frameworks and international conventions regarding hazardous cargo handling and their implementation after the Port of Beirut explosion, however, this study also failed to encompass how hazardous cargo handling poses threats to the seaport infrastructure (Malak et al., 2021). Moreover, the consequence analysis, safe distance, fatality radius, and equivalent mass of explosives have also been determined for the Port of Beirut. Still, the multifaceted infrastructure risk posed to the port remained unexplored in this study (Yu et al., 2021a). In this regard, the nitrocellulose ignition, crater size, and overpressure against distance were also used to analyze the consequences of the Tianjin port explosion. Though it was a multiapproach holistic case study, it also failed to encompass the risk posed by hazardous cargo operations to the seaport infrastructure (Yu et al., 2022). Similarly, to assess the hazard for large yield explosions in urban environments, with an emphasis on the Port of Beirut explosion, a simulation study was conducted to determine the post-explosion structural damage through a finite element analysis approach-based software. Block explosion tests were also conducted for complex urban environments, however, this study was also limited in its scope to cover the diverse infrastructural risk dynamics and measures to mitigate these risks (Hu et al., 2023). These studies and events reveal a pressing need for targeted risk assessments that can address the unique challenges posed by hazardous cargo, including the potential for accidents and environmental contamination (Chen et al., 2020b).

1.2. Risk factors

The investigations on determining the roles of various causation factors for maritime and seaport accidents have remained a matter of interest for academia and industry. The major factors that endanger the safety of maritime transportation and seaport logistics may stem from several fundamental parameters. In this regard, the most prominent causation factor is the human, which has been investigated from several perspectives. For instance, the mechanisms of decision-making processes and priorities for setting agendas in dealing with human factors have been reviewed (Schröder-Hinrichs et al., 2013). Recommendations have been provided for the effective classification of the human factors in maritime accident causation (Galieriková, 2019). The use of data-driven Bayesian networks has been employed to determine the patterns of the human role in past maritime accidents (Fan et al., 2020a). The association development between the human element and maritime safety from the vessel traffic service operator perspective has also been established in this regard (Crestelo Moreno et al., 2022).

Another proper dimension in the causation factors is improper transportation and storage, and in this regard, a study aimed at the maritime transportation accidents of hazardous cargo revealed improper packaging, containment, and issues before loading on ships were the main accident causation factors (Ellis, 2011). Another study focused at hazardous cargo accidents in China revealed that improper loading and unloading, stowage and isolation, and tank cleaning and degassing were the most critical accident causation factors (Ma et al., 2022). A study aimed at the maritime transportation of the lithium energy battery storage system reported that ships with improper fire extinguishing and alarm systems were susceptible to severe catastrophes (Zhang et al., 2023).

Another prominent accident causation factor discussed in the literature is congestion and traffic. To evade the impact of increased port traffic and enhance safety, the multi-agent path-finding approach has been used to improve the path quality for vessels (Teng et al., 2017). Likewise, a study focused on maritime accident investigation over different geographic regions reported that high cargo volumes and route density were the critical accident causation factors (Zhang et al., 2021). A review study aimed at maritime safety reported that traffic and congestion have remained prominent accident causation factors and a point of interest for research in the relevant literature (Luo and Shin, 2019).

Fire and explosions are yet another critical concern in maritime safety as they can be associated with catastrophic accidents, also, fires and explosions are not only a type of accident, but also a causation factor to serious and devastating accidents like that in Tianjin and Beirut. Fire and explosion have remained a prominent cause and interest of investigations, and accidents across the United Kingdom, Europe, Australia, and Asia have been studied (Acejo et al., 2018; Bowo and Furusho, 2019). In this regard, a study focused on maritime fire and explosion accidents between 1995 and 2015 analyzed the causation and prevention from a technical perspective and recommended the use of alternative fuels (Baalisampang et al., 2018). While, another study investigated the fire and explosion accidents in tankers carrying hazardous cargo (Uğurlu, 2016).

The impact of corrosion on various structures and structural members has also been investigated, for instance, corrosion rate estimations have been conducted for the structural members of the single hull oil tankers (Wang et al., 2003). Corrosion rates and corrosion-induced failure risk have also been quantitatively assessed for oil transport pipelines (Taleb-Berrouane et al., 2021). However, the impact of hazardous cargo-induced corrosion on the seaport infrastructural members is rarely considered. Security is another prominent aspect of accident causation, and the threat is imminent from both physical and cyber perspectives. In this domain, the security incidents reporting, record maintenance, and incident investigation infrastructure for Mexican ports were studied through a novel framework (Ávila-Zúñiga-Nordfjeld and Dalaklis, 2019). The nonlinear relationship between port security threats and cargo volume has also been investigated (Yeo et al., 2013). Unauthorized access, theft of information, and loss of information are other critical dimensions of complex port business processes (Jović et al., 2019). Likewise, a review of the literature focused at autonomous ships reported cybersecurity as a critical concern (Chaal et al., 2023). Every causation factor mentioned above may have its root causes. For instance, corrosion in the neighborhood infrastructures could be the primary reason for failure and consequent incidents, which may stem from metal fatigue due to overuse of the structural systems (Chen et al., 2022; Monje, 2012) and lay it open for the invasion of corrosive substances. The insufficiency of knowledge about the vulnerability of the constructed systems to the chemical ingredients of the water and surrounding environments could be another reason for this problem (Ceyhun, 2014; Wang et al., 2005). The implicated changes in the concentrations of soil and water chemicals in the adjacent areas could be another possible cause of failure and subsequent incidents. In the same way, various other aspects could be investigated for root causes.

1.3. Infrastructure impact

On the other hand, it is essential to investigate the possible imposed dangers to the structures in the neighborhood. For instance, the incidents stemming from fire and explosions may intimidate the storage facilities (Tahmid et al., 2022), equipment (Gasparotti, 2010), buildings (de Lira-Flores et al., 2018), and the crew (Baalisampang et al., 2018). The concept around the seaports and the integral infrastructure and the events that endanger their safety and/or the equipment in the vicinity has a vast discussion area that is underexplored from several perspectives including the hazardous cargo. In this regard, studies have been conducted on the analysis of seaport disruption instigated by environmental and climate factors and the consequent rehabilitation and business reliance approaches have been discussed (Hossain et al., 2020; Jiang et al., 2020a). To comprehend the impact of a wide array of port infrastructure and relevant risk factors, a threat utility function was employed to quantify the impact on supply chain disruption (Do Bagus and Hanaoka, 2022). Seaports are vulnerable to natural disasters and climate change risks, and in this regard the natural risk factors and their impact on the port have been assessed in concurrence with the existing risk management policies, recommending areas for further actions (Asariotis et al., 2024). A seaport disruption risk assessment based on past data revealed weather extremities as a critical disruption factor among others (Yin et al., 2024). A study based on comparative risk prevention and adaptation analysis for seaports recommended risk adaptation as a better policy for associated stakeholders (Wang et al., 2024). Evaluating the impact of various risk factors on seaport and concomitant supply chain disruptions reported infrastructure threats as a critical risk factor for the seaport performance (Do Bagus and Hanaoka, 2023). To determine the wide-ranging impact of natural disasters and climate change on seaports, an innovative approach was employed based on the seaport's system risk capacity (Mitra et al., 2024). However, the risk to seaport infrastructure and operations posed by hazardous cargo operations is much less explored and is an imminent and critical gap in the existing literature.

1.4. BNs in maritime safety

Bayesian networks are exceptionally efficient instruments for examining data that contain uncertainties and inaccuracies. They amalgamate multiple inference methods ranging from artificial intelligence, to graph and probability theory (Wang et al., 2016). BNs exhibit remarkable proficiency in effectively handling various variables and their states within a probabilistic system using inference techniques. Consequently, BNs provide a natural and robust structure for analyzing complex decisions and risks involved in maritime transportation. It can be argued that this approach guarantees a systematic, rigorous, and dependable evaluation, offering exceptional support for decision-making (Yang et al., 2018a; Yang et al., 2018b). When utilizing this technique, it is essential to ascertain that the subject being studied is suitable and that the level of analysis is appropriate.

Subject to their predictive and diagnostic capabilities, BNs have been extensively used in maritime safety. BNs can demonstrate and capture the dependency among the factors at play, update the model once new information becomes available, incorporate and deal with intrinsic uncertainties, and employ both expert opinions and past data (Baksh et al., 2018). Subject to their capacity of integrating past data and knowledge, BNs appear as a robust tool for diagnostic and forecast operations in uncertain scenarios. These features make BN a suitable tool for multi-factor, multi-scenario intricate risk assessment. To analyze the consequence severity of maritime accidents, a novel BN-based approach was employed (Wang and Yang, 2018). Similarly, keeping in mind the entire processing chain, an innovative BN-based approach was designed to assess the piracy risk for offshore oil rigs (Bouejla et al., 2014). Risk analysis through BN models first require to develop the structure of the BN model, which can be achieved through experts, literature, learning from data, or an amalgamated approach.

In this regard, the opinions of the subject matter experts and accidents database from the International Maritime Organization (IMO) have been used for model development (Bouejla et al., 2014). The same IMO data and expert opinion-based approach has also been employed to determine the probability of ship hijacking through a BN model (Pristrom et al., 2016). Learning the structure of the BN model through machine learning employing past data has limitations of developing irrational and vague associations among the variables under consideration. To subside this limitation, expert knowledge has been employed in past studies to rationalize the sense of the developed associations (Iaiani et al., 2023). In this domain, to conduct a quantitative risk assessment for navigation in the Yangtze River, an initial BN structure was developed based on the past data, which was later verified through parameter sensitivity analysis, and associations with irrational responses were modified (Zhang et al., 2013). Similarly, a BN was introduced to assess the risk of ship accidents at sea (Akhtar and Utne, 2014). Initially, data were gathered to establish the BN framework and the related conditional probabilities. Nevertheless, because of insufficient data, expert opinions were utilized, leading to the creation of a qualitative model and its taxonomy for learning the structure. Moreover, the accident risk along the maritime silk route was quantified using BN. Both the model development and probability quantification were conducted based on past data utilizing a data-driven machine-learning algorithm (Jiang et al., 2020b).

1.5. Objective and scope

The transport of maritime hazardous cargo has a critical role in making the operations and existence of global supply chains and economy possible. However, the transshipment, handling, and overall logistics of hazardous cargo at the seaport pose a serious risk to its infrastructure as evidenced by the catastrophic accidents at the ports of Tianjin and Beirut, as discussed earlier. The seaport exhibits multifaceted and diverse vulnerabilities to the risk concomitant to the seaport's hazardous cargo operations. However, studies unequivocally focused at the seaport infrastructure risk subject to hazardous cargo operations are very rare.

To effectively mitigate these risks, seaports require a multifaceted risk assessment approach that encompasses not only the physical and operational aspects but also the environmental and human factors involved in hazardous cargo operations. This involves evaluating the potential for accidents, the effectiveness of emergency response strategies, and the resilience of infrastructure to withstand such events. However, the literature reveals a lack of comprehensive frameworks that integrate these diverse elements into a coherent risk assessment strategy for seaports handling hazardous cargo.

This research is a portion of an extensive investigation of authors focused at seaport hazardous cargo operations. Previous studies from this investigation were aimed at the risk assessment for berthing of hazardous cargo vessels (Khan et al., 2023), loading and unloading of hazardous cargo (Khan Rafi et al., 2024), post-berthing port hazardous cargo handling accident and pollution risk assessment (Khan et al., 2021a), and human factors involvement in port hazardous cargo operations accidents (Khan et al., 2022; Khan et al., 2021b). In this domain, to the best of the author's knowledge, the literature on port infrastructure risk subject to hazardous cargo operations is very scarce lacking noticeable studies.

This study aims to fill this critical gap by proposing a holistic risk assessment framework tailored to the needs of seaports dealing with large volumes of hazardous cargo. The multifaceted impact and vulnerability of hazardous cargo operations have been attempted to capture through a holistic approach considered in this study encompassing the aspects of inappropriate handling, inadequate planning, lack of capacity and resources, associated congestions and traffic augmentation, corrosion and contamination, fire and explosion risks and the concomitant safety and security risks. By leveraging expert opinions, accident reports, and advanced analytical techniques like BNs, this research seeks to provide a comprehensive understanding of the risks involved and offer practical solutions for enhancing seaport safety and resilience. In doing so, it contributes to the body of knowledge by addressing a significant and underexplored area of maritime safety and risk management.

2. Methodology

As a blend of graph theory and probability theory, BNs can serve as an effective tool for analyzing the interconnections and uncertainties associated with these variable factors (Pearl, 2003). BNs utilize a quantitative approach towards risk assessment, offering practical outcomes. They are becoming more popular as a tool for supporting causal inference (Hänninen, 2014). The advantages of BNs in this field are particularly notable, as they are effectively applied to address the significant uncertainty inherent in maritime safety. Moreover, its ability to integrate data with expert insights helps overcome the limitations of data quality and availability in maritime safety and accident analysis. The practical effectiveness of BNs is enhanced by their capacity to revise models as new evidence becomes available. Additionally, characteristics like adaptive modeling, the capability for continuous updates, and the integration of hidden variables enhance the realism and logic of using BNs for maritime safety and risk management (Hänninen, 2014). In a BN, the connections between different indicators of an undesired event can be identified, allowing the most significant aspect to be recognized. The distinctive features of a BN involve its capacity to perform inverse inference, incorporate new information into the network, utilize probabilistic semantics to manage incomplete or missing data, and provide a graphical representation of the unique cause-and-effect relationships (Anon, 2024, Ren et al., 2009, Ren et al., 2008, Yang et al., 2018b). BNs can effectively perform inferences using both fixed and stochastic data, offering a versatile modeling framework for complex interdependent variables (Xie and Waller, 2010). Due to these numerous advantages, BNs have been applied across various fields, despite not being a new method. A brief overview of the popularity and acknowledgment of the BNs in contemporary maritime safety and risk-related literature is presented in Table 1.

Table 1
A brief overview of the applications of BN in maritime safety.

Author and year	Approach	Key Area
(Tunçel et al., 2024)	A rule-based Bayesian network extended evidential reasoning approach	Comprehensive risk assessment for anchoring operations in maritime transportation.
(Chen et al., 2022)	Evidence-based fuzzy Bayesian network approach for probabilistic models	Quantitative roles of causation factors-based risk assessment for marine accidents.
(Li et al., 2024)	A data-driven Bayesian network approach	A dynamic pattern comparison of changes in maritime accidents.
(Fan et al., 2024)	A novel object-oriented Bayesian network approach	Risk assessment for traditional and piracy accidents in maritime transportation.
(Öztürk et al., 2024)	A fuzzy Bayesian network modeling approach	Human error impact assessment in the master-pilot information exchange induced maritime accident risks.
(Göksu et al., 2023)	A Fuzzy-Bayes network approach	Risk assessment and investigation of the root causes for ship steering gear failure accidents.
(Fan et al., 2020c)	A Bayesian network and TOPSIS-based multicriteria decision-making approach	Human factor-induced maritime accidents prevention strategy.
(Kaptan, 2022)	A Fuzzy logic-based Bayesian network approach	Accident analysis for vehicle stowage on RO-RO vessels.
(Fu et al., 2022)	An accident map-Bayesian network quantitative analysis framework	Risk assessment for grounding accidents in Arctic waters.
(Fan et al., 2022)	A Bayesian network model and Bayesian Search algorithm approach	Ship accident risk and safety assessment based on port state control inspections.
(Fan et al., 2020b)	A Bayesian network-based risk analysis approach	Analysis of factors impacting maritime transport accidents.
(Li et al., 2023)	A data-driven Bayesian network-based risk analysis model	Risk analysis for global maritime accidents.
(Jiang et al., 2020b)	A Bayesian network-based risk analysis approach	Risk assessment for maritime accidents along the main maritime silk route.
(Hossain et al., 2019)	A Bayesian network-based approach for modeling resilience	Resilience quantification and assessment of port infrastructure.
(Khan Rafi et al., 2024)	An interval type-2 fuzzy Bayesian approach	Risk assessment for loading and unloading of hazardous cargo at seaports.

It can be stated that the first step towards building a BN model for scrutinizing the risk of seaport infrastructure is to develop a qualitative framework and establish interrelationships among the involved variables. Afterward, it becomes imperative to measure these relationships and validate the accuracy of probability distributions. Once accomplished, the inference system of the BN can be triggered, and model testing can be conducted to evaluate the effectiveness, efficiency, and dependability of decision-making. The complete process of modeling and assessing is executed within the Hugin interface software for BNs. This software provides a resilient and trustworthy environment for modeling probabilistic risk and carrying out inference calculations. The methodology that has been utilized is elucidated step-by-step below, and its schematic flowchart is illustrated in Fig. 1.

2.1. Finalizing nodes and causal relationship

The first and vital step in constructing a BN model is to recognize the variables associated with the research topic and how they are interrelated. The graphical representation of these variables as nodes and arcs is essential since it enables one to determine causal relationships and make inferences that would be difficult to obtain using precise equations. In the graphical representation of the model, each node on the network corresponds to a particular variable, and the causal relationship is depicted such that the independent variables are designated as parent nodes and the dependent variables as child nodes. To showcase the

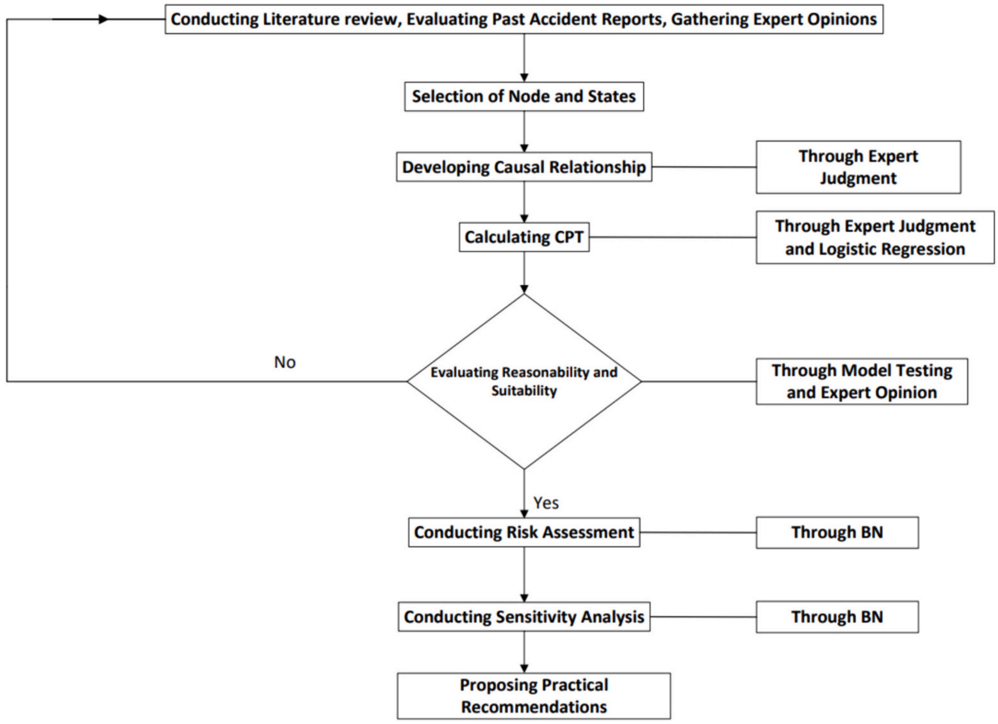

Fig. 1. Schematic graphical illustration of the adopted methodology.

causal relationship between variables, the model uses arrows that originate from the parent nodes and point towards the child nodes, indicating their interdependence.

To commence the Bayesian inference process, the availability of data is vital. Such data may be sourced from several origins, including literature, accident databases, and past models and simulations. The input of experts is integral to reaching a positive conclusion in the process, as they offer their judgment to compensate for missing data. If actual data is obtained, the expert's opinion may be revised to address any discrepancies. To increase the reliability of the modeling process, it is necessary to carefully assess the degree of uncertainty and ambiguity that arises naturally in the process, and use expert judgment and available data to refine it.

When selecting and collecting opinions of the experts, their domain qualifications and experience are of critical prominence. For this study, the domain experts were broadly classified into four main categories including the engineering (port and marine), port operators, government officials (regulatory compliance, etc.), ship crew and shipping company officials, and academic scholars. The qualification of the experts ranged from a Bachelor's degree as minimum criteria, to a Ph.D., and the minimum criteria for the experience with hazardous cargo handling and infrastructure was set as ten years. Another prominent aspect in this domain was the age of the experts, which ranged from a minimum of thirty-five years to a maximum of more than sixty years. Likewise, the profession and job title were another prominent category considered while finalizing and contacting the experts, and the prominent professions and job titles were captains, managers, chief and senior engineers, divisional directors, assistant general managers, and professors.

The description of the expert is summarized in Table 2.

2.2. Quantifying prior probabilities and CPTs

After identifying the variables and their causal relationships using a graphical format, it becomes necessary to create CPT for each node. This process may involve the use of expert judgment, available data, or a

Table 2
Description of the experts.

Category	Description	Qualification	Experience	Age (Years)	Profession/Job title
Engineering Experts	Experts in port and marine engineering	Bachelor's to Ph.D.	Minimum of 10 years in hazardous cargo handling and infrastructure.	Min-35 Max-60+	Chief Engineers, Senior Engineers, Managers
Port Operators	Individuals managing port operations.	Bachelor's to Ph.D.	Minimum of 10 years in hazardous cargo and infrastructure handling.	Min-35 Max-60+	Port Managers, Divisional Directors
Government Officials	Officials involved in regulatory compliance and policy.	Bachelor's to Ph.D.	Minimum of 10 years in relevant regulations and compliance.	Min-35 Max-60+	Regulatory Compliance Officers, Inspectors
Ship Crew & Shipping Officials	Personnel from Ships and shipping companies involved in hazardous cargo handling.	Bachelor's to Ph.D.	Minimum of 10 years in hazardous cargo operations.	Min-35 Max-60+	Captains, Shipping Managers, Assistant General Managers
Academic Scholars	Researchers and educators specializing in maritime and hazardous cargo studies.	Ph.D.	Minimum of 10 years in research related to hazardous cargo and infrastructure.	Min-35 Max-60+	Professors, Associate Professors, Senior Researchers

combination of both to ensure an accurate representation of the underlying probabilities. This study adopts expert judgment and binary logistic regression for the determination of probabilities. Logistic regression is a valuable statistical technique that utilizes a logit function to model the probability of an event happening, making it a powerful tool for predicting outcomes based on available data. It is widely acknowledged as an effective diagnostic method for multivariate analysis of categorical dependent variables (Khan et al., 2021c; Li et al., 2014).

Logistic regression is specifically designed for modeling binary outcomes, which is suitable for predicting accident occurrence (binary outcome of 0 and 1 for the current study) based on expert judgments of factors A, B, and C. In our example, the outcome variable is whether an accident occurs (1) or not (0) at a seaport. Logistic regression is ideal for predicting this binary outcome based on expert judgments of factors like insufficient capacity, poor infra design, and deficient emergency systems. Logistic regression models the probability of the occurrence of an event (in this case, accidents) rather than predicting a continuous outcome, assuming a non-linear relationship between the predictor variables of the mentioned factors and the outcome (Inadequate planning), allowing for more complex relationships to be captured. This aligns with the nature of the problem, where we are interested in estimating the probability of accidents based on expert judgments of various factors considered in the model. It also models the log odds of accidents, ensuring that the predicted probabilities are within the range of 0 to 1. This transformation is crucial for predicting probabilities, as probabilities outside this range wouldn't make sense in our context. Logistic regression is robust to outliers in the expert judgment predictor variables of factors. Outliers in the predictor variables won't heavily influence the predictions, ensuring more reliable estimates.

Logistic regression provides a structured framework for efficiently quantifying expert judgments on the role or probability of each factor in accident causation. By assigning scores or probabilities to each factor considered in the model, experts can provide their assessments in a standardized and quantitative manner. Experts from various backgrounds including port authority officials, terminal operators, ship crew, port infrastructure engineering staff, and personnel from relevant backgrounds provide their assessments of each factor's importance in accident causation and posed risk to the seaport infrastructure, for example, using a scale from 1 to 5, where 1 indicates low importance and 5 indicates high importance. Logistic regression quantifies these expert judgments by assigning numerical values to each factor based on the experts' assessments. For instance, a factor, say "Inappropriate Handling" of hazardous cargo, with an average score of 4 from experts would be assigned a higher weight in the logistic regression model compared to a factor, say "Poor Infrastructure Design" with an average score of 2.

It produces interpretable coefficients that represent the impact of each factor on accident probabilities. This allows stakeholders to understand the relative importance of different factors based on expert judgments, facilitating informed decision-making. The logistic regression model produces coefficients for each factor, indicating their impact on the probability of accidents. A higher coefficient suggests that a factor has a more significant influence on accident and infrastructure risk likelihood based on expert judgments. For example, if the coefficient for "Inappropriate Handling" is 0.8, it means that for every one-unit increase in the expert-assessed importance of inappropriate handling (on a scale of 1 to 5), the odds of accidents or infra risk occurring increase by a factor of exp. (0.8) ≈ 2.23.

It systematically integrates expert judgments into a single predictive model. This enables stakeholders to aggregate and synthesize diverse perspectives from multiple experts, providing a comprehensive assessment of accident causation factors. For instance, if three experts provide scores of 4, 3, and 5 for "Inappropriate Handling" respectively, the logistic regression model aggregates these scores to estimate the overall importance of inappropriate handling in accident causation.

It also supports an iterative process of model refinement based on feedback from experts. Stakeholders can iteratively adjust the model based on new insights or changing expert opinions, ensuring that the final probabilities reflect the collective expertise of the experts involved. For example, if a new expert joins the assessment and assigns a score of 2 for "Inappropriate Handling", stakeholders can update the logistic regression model to incorporate this new input and reassess the probabilities of accident or risk causation factors. Within this context, the primary aim of the investigation is to examine the variables and their influence on the likelihood of seaport infrastructure disruptions occurring, utilizing logistic regression analysis as a means of statistical inquiry.

In a binomial model denoted by y, the probable consequences of the infrastructure risk and disruption are illustrated such that $y = 1$ stands for incidence and $y = 0$ denotes non-incidence. Likewise, for the execution of binary regression, a latent variable y^* is mapped onto a binomial variable y in a way that $y \epsilon (-\infty, +\infty)$. However, as the reflection of y^* is unviable, its illustration is depicted as,

$y = 1$ represents infrastructure disruption risk, such that $y^* > 0$, while.

$y = 0$ represents the non-incidence of infrastructure disruption risk such that $y^* \leq 0$.

For the situation under study where each aspect of the causation of seaport infrastructure risk with a variable X such that it has n dimensions as $X = (x_1, \ldots, x_n)$, considering y^* a function of X can be illustrated as,

$$y^* = X\beta + \mu \tag{1}$$

The diverse aspects of the risk and their causation would constitute a matrix and also the unknown parameters coefficient being represented by β, the result will be as,

$$E(y|X) = P(y = 1|X) = P(y^* > 0|X) = P(\mu > -X\beta) = 1 - F(-X\beta) \tag{2}$$

The above depicted function has the capacity of adoptability into a wide array of forms, so for the existing study the logistic cumulative distribution function is implemented. Therefore, the model can be mathematically represented as,

$$P = \frac{e^{X\beta}}{1 + e^{X\beta}} \tag{3}$$

2.3. Quantifying posterior probabilities

The fundamental functionality of BN is based on probability and graph theory. Also, a significant feature of the BN is its facilitation of bi-directional information flow. This aspect imparts the capacity to observe the variations in probabilities of a node subject to the impact of prior and posterior data or knowledge. The determination of required probabilities for appropriate functioning of the BN is achieved by the incorporation of following equations.

$$P\left(Y = y_q, X_p = x_{pq}\right) = P(X_p = x_{pq}) \times P\left(Y = y_q | X_p = x_{pq}\right) \tag{4}$$

$$P\left(Y = y_q\right) = \sum_{q}^{n} P(X_p = x_{pq}) \times P\left(Y = y_q | X_p = x_{pq}\right) \tag{5}$$

$$P\left(X_p = x_{pq} | Y = y_p\right) = \frac{P(X_p = x_{pq}) \times P\left(Y = y_q | X_p = x_{pq}\right)}{P\left(Y = y_q\right)} \tag{6}$$

Where Eqs. (4)–(6) are the illustration of the joint probability distribution, marginalization rule, and Bayesian rule respectively. Hence, in the existing study, the β values are acquired from the binary logistics regression, while the conditional probabilities are quantified using Eq. (5). Finally, the desired outcomes are acquired from Eq. (6) utilizing the expert judgments for the selection and valuation of factors and aspects

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under consideration.

However, to enhance the understanding of CPT calculation, a solved example is provided from the situation under investigation. Considering a simple network where the seaport infrastructure is at risk subject to the fire and explosion instigated by a hazardous cargo incident. For the situation under consideration, the probability of seaport infrastructure risk is given in Table 3.

The seaport infrastructure may face a disruption subject to the fire and explosion instigated by hazardous cargo. Therefore, under the impact of fire and explosion, the seaport infrastructure risk probability is given as follows in Table 4.

In the current scenario, the probability of a fire and explosion impact can be quantified using Eq. (5) as depicted below,

$$\text{P (Fire and Explosion impact)} = (\text{P (Fire and Explosion |No seaport risk)*P (No seaport risk)}) + (\text{P (Fire and Explosion | Seaport risk)*P (Seaport risk)}) = ((.1^{*}0.7) + (0.95^{*}0.3)) = 0.35$$

To calculate the probability of seaport infrastructure risk under the impact of fire and explosion Eq. (6) is utilized and illustrated below.

$$\text{P (Seaport infrastructure risk |Fire and explosion)} = \{\text{P (Fire and explosion |seaport Infrastructure risk)}^{*}\ \text{P (Seaport infrastructure risk)}\} / \text{P (Fire and explosion impact)} = (0.95^{*}0.3)/0.35 = 0.81$$

2.4. Model validation

In the domain of risk analysis and assessment through BNs, it is of profound prominence to evaluate the plausibility of the developed model by subjecting it to certain validity tests defined in the literature. In the existing study, the developed model is validated through sensitivity analysis of varying the input values and observing the consequent changes. Henceforth, the below-mentioned conditions have to be met by the developed model in order to be considered valid and worthy of conducting the seaport infrastructure risk analysis.

1. A variation in the initial probabilities of the parent node shall induce a germane consequent change in the probability of the child nodes.
2. The variation induced in probabilities of parent nodes shall induce a concurrently consistent variation in the posterior probabilities of the child node.
3. The third condition is that the value of the total impact generated by the combined probability variations of the x attributes should always remain greater than that of a set of *x-y (y ϵ x)* (Liu and Liu, 2019).

3. Seaport hazardous cargo infrastructure risk

The efficient functioning of seaport operations is of paramount importance to the global supply chain, particularly in the transport of hazardous cargo. As gateways for the import and export of such goods, seaports play a vital role in facilitating their safe and secure movement between countries. Their seamless operations ensure the effective and efficient transportation of hazardous cargo, reducing costs and enhancing the speed of delivery. This, in turn, minimizes the risk of delays and potential safety hazards, safeguarding the global supply chain. Seaports also support industries such as chemicals, oil and gas, and manufacturing that rely heavily on the safe and secure transport of hazardous cargo, promoting their growth and development. In addition to supporting international trade and economic growth, seaports are critical to the development of other sectors such as tourism, fisheries, and offshore oil and gas. However, disruptions to seaport operations and overall logistics can result in significant financial losses, safety hazards, and environmental damage, impacting both the local and global economies. Therefore, the efficient functioning of seaport operations is essential to the growth and development of hazardous cargo transport and the overall safety and security of the global supply chain.

However, the complex seaport hazardous cargo operations pose a significant multifaceted threat. Among other risk aspects, the manifold impact on the seaport infrastructure is a matter of critical concern and yet very scarcely explored. Any damage to the seaport infrastructure in the wide array of its functionality has the potential to hamper the entire operations and overall logistics of the seaport instigating a partial or entire closure of the port. Such disruptions play a havoc to the entire supply chains along the regional and global economies. Therefore, to ensure the seamless functioning of the seaport infrastructure and hence the port whilst facilitating the hazardous cargo operations, this study considers a wide array of impacts of hazardous cargo operation on the seaport infrastructure, which, in turn, act as potential seaport infrastructure risk causation factors, to conduct a holistic seaport infrastructure risk analysis. Comprehension of each aspect of the impact and hence the factor and their likelihood are pivotal in the conducting holistic risk assessment and henceforth developing a risk management plan that will circumvent the impact of hazardous cargo operations on the seaport infrastructure damages and disruptions. This, in turn, will contribute towards the seamless seaport operations and hence facilitate the supply chain and economy at both local and global level.

Table 3
Seaport infrastructure risk probability.

Port infrastructure risk	Probability
No	0.7
Yes	0.3

Table 4
Port infrastructure risk under the effect of fire and explosion.

Port Infrastructure risk	No	Yes
Fire and explosion "no"	0.9	0.05
Fire and explosion "yes"	0.1	0.95

3.1. Establishing nodes and BN model

In consultation with subject matter experts, relevant literature (Molero et al., 2017; Shafieezadeh and Ivey Burden, 2014; Lam and Lassa, 2017; Verschuur et al., 2020; Hossain et al., 2020; Hossain et al., 2019; Rose et al., 2018; León-Mateos et al., 2021; Popek, 2019; Khan et al., 2021c; Hua et al., 2021; Khan et al., 2021a), and a meticulous evaluation of the past accident reports a list of the potential impacts and risk contributing or causation factors and sub factors of the seaport hazardous infrastructure risk have been finalized. A brief description of the factors under consideration has been provided here to augment the comprehension of the scenario under consideration.

a. Inadequate planning and risk assessment: This factor accounts for situations where a seaport starts or is conducting hazardous cargo operations, however, it does not have appropriate planning and risk assessment mechanisms in place for it. The sub-factors considered in this domain include the insufficiency of handling measures and capacity, which means the handling capacity and resources of the port are not enough and up to date as required. The second sub-factor in this domain is the lack of a contemporary, technologically advanced, and holistic emergency preparedness and response system. The third sub-factor considered in this domain stand for the port infrastructure and its design being inappropriate and poor for the facilitation of safe, smooth and resilient hazardous cargo operations.
b. Inadequate handling and storage: This factor stands for the inappropriate handling and storage of hazardous cargo in a port environment lacking the implementation and existence of developed rules, regulations, codes, and safety procedures. This factor has been divided into three sub-factors. Spills and leaks account for the spillages and leakages of hazardous cargo during the berthing, loading and unloading, piping, storage, warehousing, and transshipment at a port. The second sub-factor considered in this domain is the contamination that occurs during poor handling and accidents of hazardous cargo that not only contaminate the port waters but also contaminate the soil, air, and underground water and impact the seaport functionality in a multifaceted way. The third sub-factor considered in this domain is the structural damage that accounts for the direct structural damage caused to seaport infrastructure caused by operations and accidents of the hazardous cargo.
c. Congestion and increased traffic: This factor account for the increased traffic and traffic congestion that arise as a result of the hazardous cargo and hazardous cargo induced disruptions. In a sense, this factor accounts for the traffic generated by the seaport's hazardous cargo operations. Since the increased traffic generates further issues, this factor has been divided into two sub-factors. The first sub-factor accounts for the increased accident risk, while the second sub-factor accounts for the structural damage caused by the excessive traffic.
d. Fire and explosion: This factor represent the fires and explosion instigated by the hazardous cargo operations at ports. This factor has been divided into four sub-factors. The first sub-factor represents the damage caused to the port storage and warehouse facilities. The second sub-factor depicts the damage caused to the port equipment, specifically the cargo handling equipment. The third sub-factor stands for the damages incurred by the port buildings. While the fourth sub-factor included under this category stands for the damaged and affected personnel.
e. Corrosion: This factor represents the corrosion and the impact of chemical contents in port waters, air, and soil on the port infrastructure. It has been divided into three sub-factors. The first factor represents the degradation faced by the overall port infrastructure and resources over time due to prolonged chemical exposure. The second sub-factor considered in this domain is the increased maintenance and associated costs. The third sub-factor stands for the increased vulnerability of equipment, personnel, and cargo as the equipment and buildings incur a continuous degradation, hence the equipment, cargo being handled and personnel are at an increased safety risk.
f. Security issues: This factor stands for the security risks and issues concomitant to hazardous cargo operations. The first sub-factor considered in this domain is the risk of terrorism and sabotage that inflicts damages on the port equipment, infrastructure, and business stature. The second sub-factor considered in this domain accounts for the associated losses of personnel or manpower.

All the root and intermediate nodes and the seaport infrastructure risk nodes in this study are taken as binary nodes having two states state

Table 5
Example pattern of survey questionnaire.

Impact assessment of inadequate planning		
Level of infrastructure resource	Reasonability of the design	Ability to withstand and handle emergency
Probability:	Probability:	Probability:

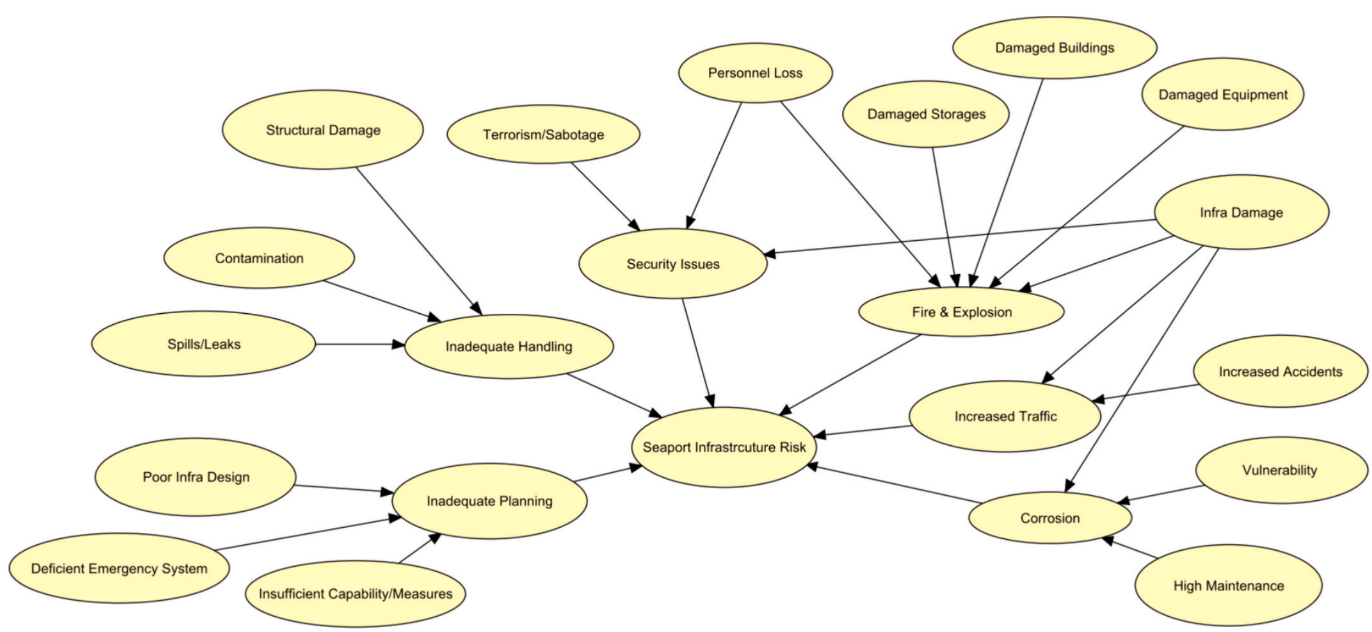

Fig. 2. DAG of the seaport infrastructure risk model.

"0" and state "1". The state "0" represents non-occurrence or no impact for a certain node or factor, while the state "1" stands for the occurrence and impact of the node or factor. After the finalization of the factors and sub-factors, the causality relationship or association between them was developed in consultation with the subject matter experts resulting in a model for the seaport infrastructure risk. The directed acyclic graph of the developed BN model for seaport infrastructure risk has been presented in Fig. 2.

The expert judgment was gathered through an electronic survey questionnaire which was sent to the subject matter experts in academia and industry in both terminals and port management from the public and private sectors, for which the details are shared in methodology section. The response gathered was evaluated for completeness and viability, and considered for study after meeting the criteria. However, the original survey was conducted in Chinese, and the authors have tried to provide an example of the employed survey questionnaire with the nearest matching translations of that in Table 5.

3.2. Model validation

In the domain of cause consequence and cause-cause analysis, BNs are considered a robust tool subject to their capacity to facilitate the bidirectional flow of evidence and inference. Once the prior probabilities and CPTs have been quantified using the described methodology encompassing expert judgment, binary logistic regression, and the Bayesian equations, the data is fed into the developed DAG model. However, prior to proceed with the results analysis it is of critical prominence to validate the plausibility and suitability of the developed model. Therefore, in the existing study, the developed model was validated for all the three axiom criteria defined in the methodology.

In concurrence with the first condition or Axiom 1, a relative increase or decrease in the prior probabilities of the parent nodes shall instigate a proportionate increment or decrement in the posterior probabilities of the child node. The variation results presented in Table 6 depict a presumable performance of the BN model as alterations in the prior probabilities of the parent nodes at prior, 100 % and 0 % induce a corresponding change in the posterior probabilities of the child node, which is "Inadequate Handling" in this case. For instance, if the probability of spills and leaks increases, this will lead to an increase in the probability of hazardous cargo inadequate handling (child node) occurring. Conversely, if hazardous cargos are dealt with more professionally as per the standard operating procedures improving the safety conditions, the probability of contamination may decrease accordingly minimizing the incidence of inadequate handling. This demonstrates how variations in the initial probabilities of parent nodes induce relevant changes in the probabilities of child nodes, reflecting real-world cause-and-effect relationships within the port environment.

Likewise, condition 2 or Axiom 2 dictates that a varying number of alterations and increments in the prior probabilities of the parent node shall induce a corresponding consistent variation in the posterior probabilities of the child node. In this case, the test conducted on the node "Corrosion" is depicted in Fig. 3, which indicates that the changes induced in the posterior probability of the child node as a result of variations made in the parent nodes, do not exhibit any outliers and sharp knees, hence indicating a presumable performance of the model. This is a clear indication of the scenarios that the increase in the lack of maintenance, increased vulnerability, and higher infra damage over prolonged exposure would increase the probability of corrosion, which in turn would intensify the seaport infrastructure risk from both the incidence likelihood and consequence severity perspectives.

Table 6
Model validity test of condition 1/Axiom 1 for the node "Inadequate Handling".

Condition	Parent node	Child node
	Spills/Leaks	Inadequate Handling
Exist/State 1	Prior %	5.61
	100 %	12.2
	0 %	2.7
	Contamination	Inadequate Handling
Exist/State 1	Prior %	5.61
	100 %	8.91
	0 %	2.3
	Structural Damage	Inadequate Handling
Exist/State 1	Prior %	5.61
	100 %	14.49
	0 %	2.9

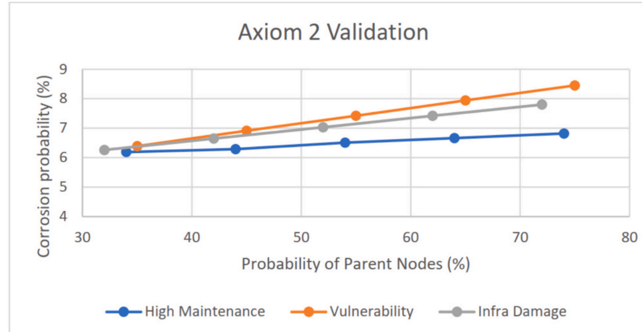

Fig. 3. Model validity results for condition 2/Axiom 2 for the node "Corrosion".

Table 7
Model validation results for condition 3/Axiom 3 for the node "Inadequate Planning".

Parent node			Child node	Percent change
Insufficient capability/ measures %	Deficient emergency system %	Poor infra design %	Inadequate planning %	
15	20	12	4.8	0 %
100	20	12	7.41	54.37 %
15	100	12	7.23	50.62 %
15	20	100	13.06	172.08 %
100	100	100	30	525 %

The third condition or Axiom 3 dictates that for a child node with more than one parent node, the combined impact generated on the posterior probabilities of the child node by changes in the prior probabilities of all the parent nodes at the same time shall always be higher than the impact generated by variations in the individual parent nodes. This validity test conducted on the node "Inadequate Handling" is presented here in Table 7, which clearly indicated concurrence with the set condition of the model validity as the combined effect of all the parent nodes is much higher than that of the individual parent nodes.

The interplay between insufficient capability to handle hazardous cargo, a deficient emergency system, and poor infrastructure design exacerbates inadequate planning for hazardous cargo handling at the seaport, consequently amplifying the risk for seaport infrastructure. Firstly, insufficient capability implies a lack of resources, expertise, and procedural protocols necessary for safe cargo handling practices. This shortage may lead to rushed or improvised handling procedures, increasing the likelihood of errors, spills, or accidents during cargo operations. Secondly, a deficient emergency system compounds the risks by impeding the port's ability to respond promptly and effectively to incidents. Without adequate emergency protocols, personnel training, or equipment, the port may struggle to contain and mitigate the consequences of hazardous cargo incidents, exacerbating their impact on infrastructure and the surrounding environment. Lastly, poor infrastructure design introduces vulnerabilities that further heighten the risk. Structural weaknesses, inadequate containment measures, or inefficient layout designs may exacerbate the consequences of mishandled cargo, increasing the likelihood of structural damage, environmental

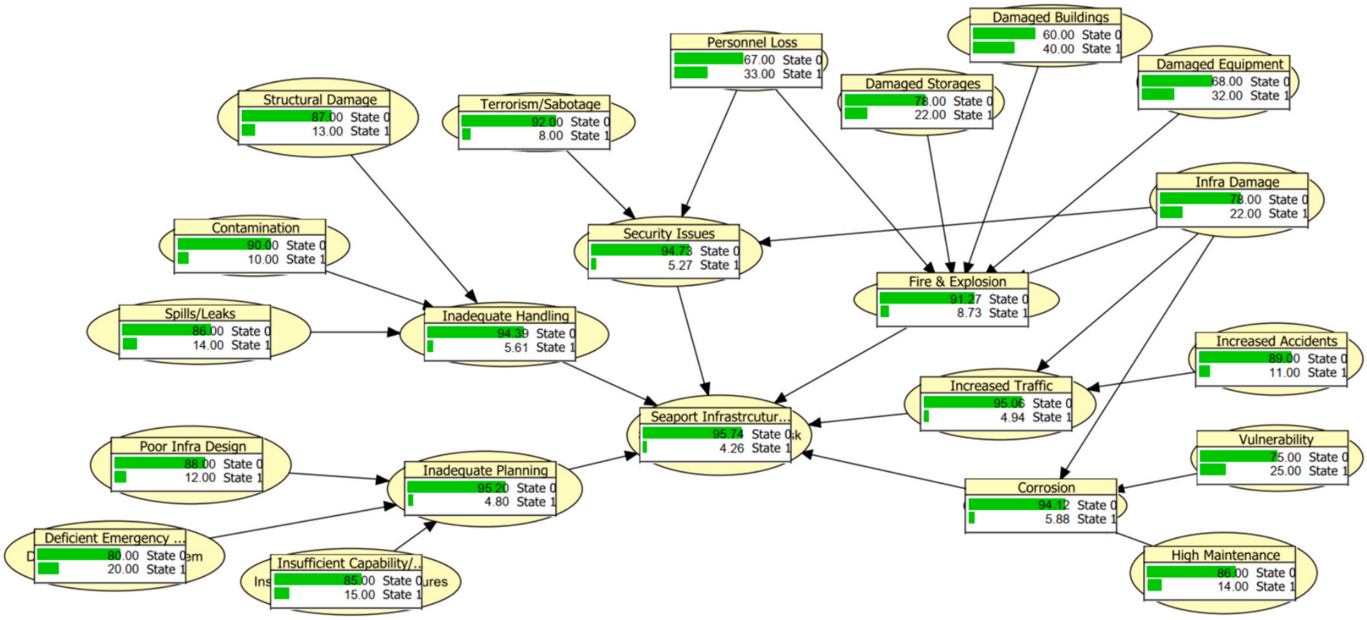

Fig. 4. Model inference results excluding any evidence criteria.

contamination, and disruptions to port operations. In summary, the combination of these three shortcomings and their combined effect intensifies inadequate planning for hazardous cargo handling more than the impact of individual factors, hence magnifying the risks to seaport infrastructure and necessitating comprehensive risk management strategies to mitigate potential hazards.

The model validity tests as per the defined conditions in the three axioms were performed for the developed model and the results indicated a satisfactory presumable performance. After the model was found credible meeting and satisfying the set validity conditions, the model was proceeded with for further analysis.

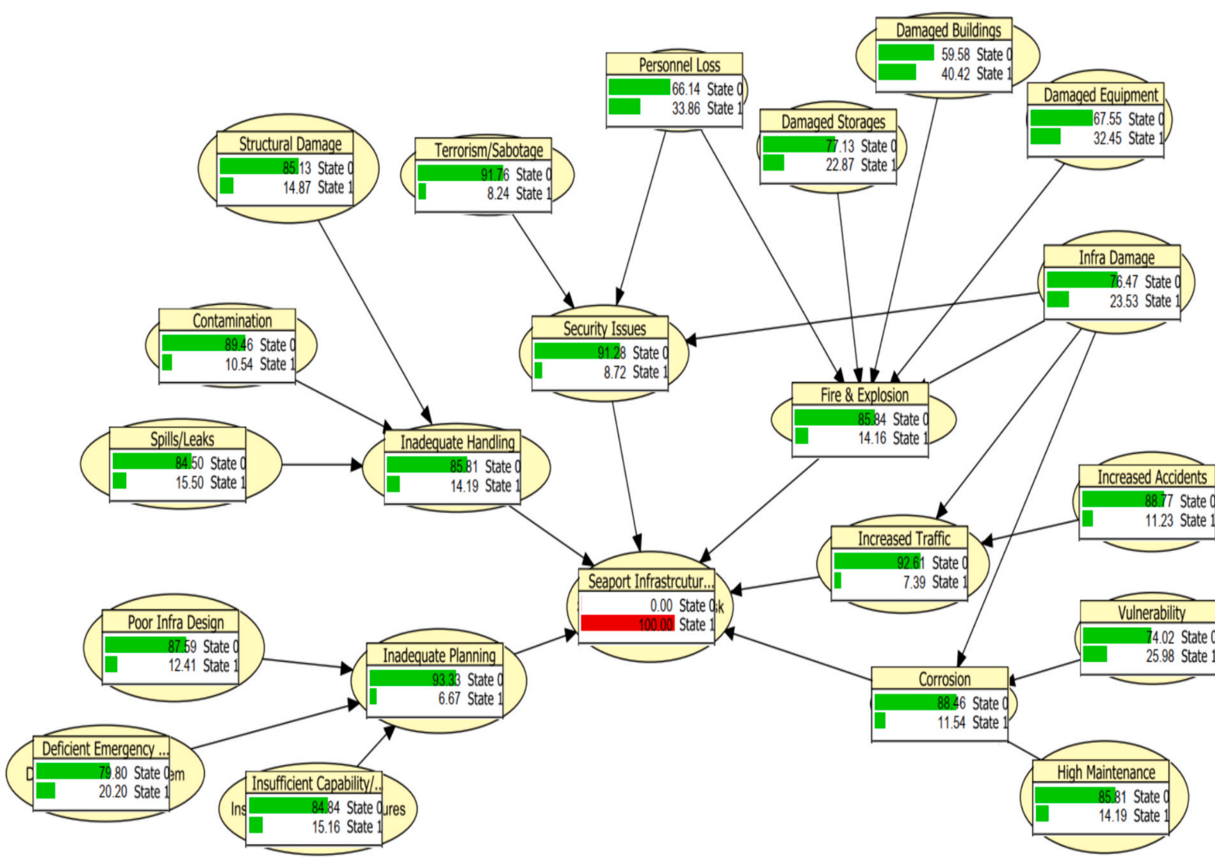

Fig. 5. Inference results for evidence set at seaport infrastructure risk.

3.3. Results analysis

After model validation, it is turned into run mode in the Hugin environment to conduct the inference analysis. As evident from Fig. 4, the seaport infrastructure is subject to a risk probability of 4.26% under normal operating conditions of the seaport hazardous cargo. Where fire and explosion, corrosion, and inadequate handling of the hazardous cargo remain the highest threats to seaport infrastructure risk with a probability of 8.73 %, 5.88 %, and 5.61 % respectively. While the impact of security issues and traffic congestion cannot be ignored either. At the root node level, damaged buildings and personnel loss along with the resultant manpower shortages and technicality, caliber, and experience compromise a resultant impact on the hazardous cargo operations are the highest contributors of the seaport infrastructure with the probability of 40 % and 33 % respectively. Similarly, the damaged and impacted equipment is another prominent infrastructure risk with a probability value of 32 %. Likewise, the structural and equipment vulnerability as a result of the induced hazardous cargo impact over the longer exposure is another prominent risk factor as it has a prominent role in increasing the seaport infrastructure risk because it not only puts the working personnel and equipment at risk but also the cargo being handled and the seaport equipment and buildings are also at a larger consequent risk. This corrosion and chemical-induced vulnerability have a contribution probability of 25 % towards the seaport infrastructure risk.

In the next step, the inverse propagation aspect of the BN is utilized by setting evidence at the seaport infrastructure risk increasing its probability to 100 %. As evident from Fig. 5, by setting evidence at the seaport infrastructure risk, the contribution probability of inadequate handling experiences the highest increase as its probability increases from 5.61 % to 14.19 % which is an increment of 153 % approximately. This trend clearly indicates the criticality and prominence of inadequate handling in the seaport hazardous cargo operations. A hazardous cargo inappropriately handled or mishandled can threaten the seaport infrastructure in a multifaceted way. In this domain, a recent and high-profile example is that of the Tianjin port where the mishandling of nitrocellulose and ammonia products brought upon a wreck on the whole port and its infrastructure causing huge life and environmental losses with financial losses in billions of dollars (Fu et al., 2016). The explosion at the Port of Beirut and the subsequent destruction of the port and adjacent city infrastructure is another high-profile case where the mishandling of the hazardous cargo not only destroyed the seaport infrastructure but also damaged the infrastructure and environment in the vicinity causing property losses worth 15 billion US dollars (Mehan and Jansen, 2020; Yu et al., 2021a; Malak et al., 2021). This disaster left at least 300,000 people homeless, which clearly emphasizes the criticality of seaport hazardous cargo operations and their vulnerability subject to inadequate handling. Such hazardous cargo-induced incidents not only destroy the infrastructure of seaports and vicinity, but they also contaminate the air, water, and soil in the vicinity which has repercussions of its own in the longer run.

Apart from these massive and worst-case accidents, there are abundant spills and leaks of hazardous cargo in the ports subject to mishandling. Such incidents result in dispersion clouds, structure degradation, drinking water contamination, and soil contamination which also hamper the port infrastructure stability, air contamination and also the seawater contamination. Seawater contamination is also a broad-spectrum risk which not only damage the marine life and disturb the marine ecosystem, but it also seriously impacts the seaport infrastructure exposed to seawater. The induced chemical concentrations in the seawater can hamper the resilience, stability, durability, consistency, and strength of all the structural and infrastructure components ranging from steel to wood, concrete, and earthworks. Even the minute of spills and leakages which also have the tendency to be left unnoticed have the capacity to hamper and damage the seaport infrastructure in the longer run because of the extended and diverse chemical exposure of the seaport infrastructure. In this regard, the potential and plausible chemical-induced damage to foundations, pipelines, seaport internal access and communication network, and the hinterland connectivity is also worth mentioning.

Likewise, in the occurrence of seaport infrastructure disruption and damage risk, the role of hazardous cargo-induced fires and explosions is highly significant. The probability of fire and explosion remains the second highest in its contribution towards the seaport infrastructure risk with a value of 14.16 %, which is very comprehendible as the fire and explosion pose a serious threat which is explained by earlier discussion of the Tianjin Port and Port of Beirut accidents. The probability of fire and explosion towards seaport infrastructure risk increased from 8.73 % to 14.16 %, which is a 62 % increase. Here an important addition is that this increase though significant, may not seem as high as other considered aspects, but this trend well matches the expert opinion and trends in accident reports. The interesting and prominent aspect in this domain is that the massive fire and explosion risk are low in frequency, but very high in consequence severity. Therefore, the risk profile of fire and explosion is high. Also, the small fires and explosions also result in a multifaceted impact on the seaport infrastructure, which if not handled in time can pose a serious threat of calamitous consequences and the instigation of a chain reaction towards a massive accident.

The third highest contributor to the seaport infrastructure risk through the inverse propagation is corrosion. The contribution or incidence probability of corrosion towards seaport infrastructure risk increased from 5.88 % to 11.54 % which is a 96 % increase. This trend in results clearly indicates the prominence of chemicals-induced corrosion and the subsequent increased vulnerability for the seaport personnel, equipment, and cargo along the infrastructure itself. This is an oxymoronic scenario where at one end the maintenance and associated costs, time, efforts, and energies increase in resolving the issues instigated by corrosion. While, at the other end any compromise, negligence, or missing out on the corrosion ingress during checks and investigations can seriously hamper the safety of the involved manpower, equipment, and the cargo itself. The deterioration and rusting of steel members in buildings and equipment, the damage to connectivity and communication infrastructure, and the speeded spalling of concrete members are some of the resulting issues of hazardous chemical exposures. Such a situation can lead to the instigation of a serious issue by the onset of a chain reaction towards a catastrophe, and also massive damage to the seaport infrastructure and the adjacent neighborhoods.

Continuing the infrastructure risk inference analysis, the next step was to identify the factor that caused the highest increase in the incidence of seaport infrastructure risk when set evidence. In doing so, the evidence was set at all the possible aspects and factors under consideration for seaport infrastructure risk one by one and the results were analyzed. The highest increase is induced by the inadequate handling of the hazardous cargo which increases the seaport infrastructure risk from 4.26 % to 10.79 %, as evident from Fig. 6. Likewise, the impact of spills and leaks and the associated structural damage also underwent a substantial increase in their incidence and contribution probability. This trend in results is very promising as it is supported by the trends observed in accident reports and the opinion of the subject matter experts. The inadequate handling of hazardous cargo at ports while doing the loading and unloading, transshipment, temporary storage, and warehousing is a highly sensitive and critical matter and majority of the accidents are being reported to have been instigated by this. It is revealed and acknowledged as a root cause for a variety of disruptions in the seaport operations and maritime supply chain. An overview of the past accidents like Tianjin Port and the Port of Beirut, as discussed earlier reveal that inadequate handling and negligence can result in the destruction of ports and adjacent communities. This destroys the seaport infrastructure and halts the operations either partially or entirely. The seaport hazardous cargo accidents have such a nature that the full recovery of the calamitous damages induced by it can take ports and port authorities years and decades. Though the infrastructure may be

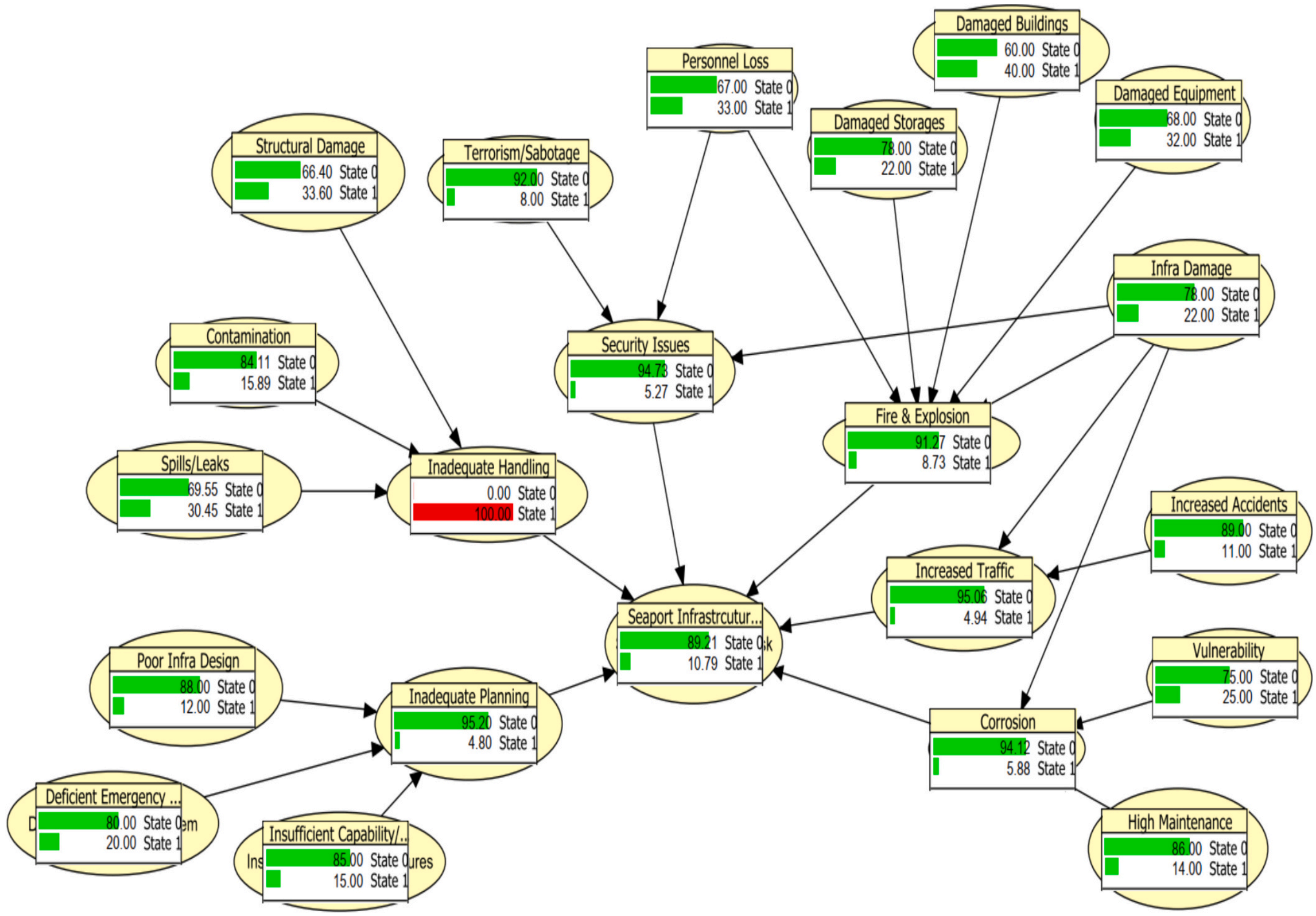

Fig. 6. Inference results for evidence set at inadequate handling.

recovered through reconstruction and redevelopment over a period of time, however, the damage to the stature of the port and its business image is irreversible. Such massive accidents onset by matters of negligence reflect the general aptitude of the involved stakeholders towards the dealing of the hazardous cargo, as the safety of hazardous cargo is a matter of grave concern and critical prominence. The confidence in the handling ability and capacity of the involved parties and authorities is sabotaged, as such accidents consequently disrupt the associated supply chains, which in turn have grave monetary and service repercussions.

The findings of this study align with critical insights from the literature on hazardous cargo accidents at seaports, particularly in the context of the Tianjin port explosion and the Port of Beirut disaster. A key concern identified in this research is the inadequate handling of hazardous cargo, which has been repeatedly highlighted as a primary cause of catastrophic incidents. Both the Tianjin and Beirut disasters underscore the lethal consequences of improper storage and handling practices (Cao and Lam, 2019; Hu et al., 2023). In Tianjin, the improper transportation of hazardous materials led to a devastating explosion, mirroring the Port of Beirut, where the negligent storage of ammonium nitrate culminated in one of the most powerful non-nuclear explosions in history (Malak et al., 2021; Fu et al., 2016). These cases illustrate the critical need for stringent handling protocols and operational oversight to prevent such high-stakes failures.

Another salient factor identified in this study is the corrosion of equipment and infrastructure caused by exposure to hazardous materials. While the investigations of both the Tianjin and Beirut case primarily focus on the immediate causes of the explosion, the broader implications of infrastructure degradation are implicit, as poor maintenance and inadequate storage conditions can significantly heighten the risk of accidents. Similarly, in Beirut, though not directly instigated by corrosion, but the extended neglect of hazardous materials storage in substandard conditions exemplifies how infrastructure degradation can contribute to catastrophic outcomes. These incidents underscore the necessity for rigorous maintenance regimes and the implementation of robust safety standards to mitigate risks associated with aging or compromised infrastructure.

Fire and explosion risks, prominently highlighted in this research, are further validated by the tragic outcomes at both Tianjin and Beirut. In both cases, the lack of proper safety measures and emergency preparedness played a critical role in exacerbating the incidents. The Tianjin port incident initially instigated by a fire led to multiple explosions and resulted in the catastrophe the world witnessed (Hua et al., 2021; Huang and Zhang, 2015). The Beirut explosion, much like the Tianjin disaster, highlights the severe consequences of explosions and fires where the entire port city had to face the devastating consequences. In both these cases, the fire and explosion were also initially instigated and their severity was augmented by inadequate risk management and emergency response capabilities when dealing with hazardous cargo. This reinforces the need for comprehensive safety protocols, particularly in the handling and storage of high-risk materials (Wang et al., 2018).

The study also identifies increased traffic and cargo volume as significant risk factors, a finding that resonates with the literature on both Tianjin and Beirut. As the volume of hazardous materials increases, so do the complexities and risks associated with their management (Liu et al., 2019). The correlation between higher cargo volumes and elevated risk profiles necessitates a more sophisticated approach to risk management, including enhanced regulatory oversight and advanced

Table 8
Percent change sensitivity analysis results.

Variable	Minimum	Maximum	Percent change
Inadequate handling	3.88	10.79	178
Corrosion	4.01	8.37	109
Fire and explosion	4.01	6.92	73
Security issues	4.11	7.06	72
Increased traffic	4.15	6.38	54

logistical planning. As the increased traffic and higher volumes put an increased burden on challenges the port infrastructure and personnel in several ways to meet efficiency requirements.

3.4. Sensitivity analysis

Sensitivity analysis is prominent in BNs because these models often involve complex relationships between variables and uncertain data associations. Sensitivity analysis is the process of examining how changes in the input probabilities or model structure affect the output probabilities of the network. It is an important tool for assessing the robustness and reliability of a BN model and can help identify which parameters or assumptions are most critical to the model's performance and most important to consider when making decisions based on the model. The present investigation conducted a sensitivity analysis by scrutinizing the extent to which modifications to the minimum and maximum prior probabilities of the parameters involved could elicit a percentage change in the likelihood of risk incidence. Each and every variable in the model was considered for sensitivity analysis and the results for the highly critical and sensitive factors and aspects have been presented in Table 8. The results reveal inadequate handling, corrosion and fire and explosion as the highly critical aspects and factors of the seaport infrastructure risk.

The sensitivity analysis conducted in this study reveals critical insights into the influence of various risk factors on seaport infrastructure risk, particularly when contextualized against real-world disasters such as the Tianjin and Beirut port incidents. The analysis shows that the probability of inadequate handling when increased from 0 % to 100 %, results in a substantial 178 % rise in seaport infrastructure risk. This dramatic increase highlights the pivotal role that handling practices play in risk escalation. The Tianjin Port explosion serves as a pertinent example, where inadequate handling of hazardous materials led directly to a catastrophic chain reaction. This underscores the necessity for stringent handling protocols, as even minor lapses could significantly amplify the risk of such events.

Similarly, the probability of risk associated with corrosion increases by 109 % when its likelihood is adjusted from 0 % to 100 %. This finding illustrates how gradual infrastructure degradation can significantly elevate the risk over time. While corrosion was not the immediate cause of the Beirut port disaster, the prolonged neglect and inadequate maintenance of storage facilities created an environment conducive to disaster. The analysis suggests that even slowly progressing issues like corrosion can lead to substantial risks if not properly managed, emphasizing the critical need for regular inspections and maintenance regimes to prevent such scenarios.

The sensitivity analysis also shows that adjusting the probability of fire and explosion from 0 % to 100 % results in a 73 % increase in risk. Although this change is less drastic than that observed for inadequate handling or corrosion, it nonetheless highlights the significant impact of fire and explosion risks, particularly when compounded by other factors. In the Tianjin disaster, an initial fire triggered a series of explosions, demonstrating how interconnected risks can exacerbate one another. This layered impact underscores the importance of comprehensive risk management strategies that address multiple, interrelated risks simultaneously.

The sensitivity analysis indicates that increasing the probability of security issues from 0 % to 100 % results in a 72 % rise in seaport infrastructure risk. This result underscores the critical impact that security lapses can have on the overall risk profile of seaports, particularly in environments handling hazardous cargo. Security issues—such as unauthorized access, theft, or sabotage—can exacerbate existing vulnerabilities by creating opportunities for deliberate harm or disruptions. In the context of the Beirut port disaster, while security lapses were not the direct cause, the lack of effective security measures allowed hazardous materials to be stored improperly and without adequate oversight. This scenario illustrates how poor security can indirectly contribute to catastrophic outcomes by enabling or failing to prevent malicious actions or unintentional breaches. The analysis emphasizes the importance of robust security protocols, including access control, surveillance, and emergency preparedness, to mitigate the risk of deliberate or accidental incidents in seaport operations.

Lastly, the 54 % increase in risk associated with increased traffic underscores the cumulative effect of operational pressures on port infrastructure. Both the Tianjin and Beirut disasters demonstrated that higher cargo volumes complicate logistics and increase the likelihood of mishandling. The analysis suggests that managing traffic and cargo flow efficiently is crucial to mitigating these risks, reinforcing the importance of robust logistical planning and regulatory oversight in high-traffic ports.

In the context of this sensitivity analysis, the significant changes in risk probabilities underscore the crucial role of expert judgment and uncertainty quantification in probabilistic assessments. As highlighted by Zarei et al. (2024), the integration of expert insights through Bayesian approaches and structured elicitation techniques is pivotal in accurately modeling and understanding the uncertainties inherent in complex systems, such as seaport infrastructure risk management. This alignment ensures that the probabilistic variations captured in the sensitivity analysis are robust and reflective of real-world complexities. Furthermore, as (Yazdi et al., 2022) discuss, addressing uncertainties, particularly in digitalized and complex systems, is essential. Inherent uncertainties arising from system complexity, data limitations, and model assumptions must be carefully managed to ensure that risk evaluations remain accurate and reliable.

4. Practical applications

Seaport infrastructure is vulnerable to risks during handling hazardous cargo operations. Protecting the infrastructure from these risks is essential for maintaining public safety, protecting the environment, ensuring legal and regulatory compliance, and preserving the economic stability of the port and the surrounding area. A hazardous cargo accident can cause significant damage to the port infrastructure, resulting in costly repairs and potentially long-term disruptions to port operations. Besides, hazardous cargo can cause significant damage to the port and surrounding environment, including water pollution, air pollution, and soil contamination damaging the soil and structural stability which in turn endanger the port infrastructure and involved equipment. Protecting seaport infrastructure from the risks of hazardous cargo involves specialized infrastructure, equipment, and personnel, as well as strict regulations and guidelines to ensure safe transportation and handling. Overall, protecting the seaport infrastructure from hazardous cargo risks is essential for ensuring the safe and efficient functioning of the port and minimizing the potential for damage to infrastructure and disruptions to operations. Based on the results of this study, some practical measures are proposed that can prove helpful in circumventing the seaport infrastructure risk and consequently help establish sustainable supply chains and associated economies.

4.1. Effective handling

Adequate handling of hazardous cargo at seaport has been identified as a critical risk factor. To ensure the efficient and safe handling of hazardous cargo, it is recommended to implement a comprehensive set of measures. Personnel involved in handling hazardous cargo should receive regular training and must be audited to ensure they understand the risks and how to mitigate them. A comprehensive training program covering all aspects of hazardous cargo handling, including the safe use of equipment and the proper handling of spills and leaks, should be developed. Augmented reality (AR) and virtual reality (VR) training tools should be used to provide realistic and engaging training to personnel responsible for handling hazardous cargo. Incentives should be provided for personnel who consistently follow established safety protocols, and behavioral science techniques such as positive reinforcement and feedback should be used to promote safe behaviors. To ensure that all hazardous cargo is properly handled and packaged, a quality control program should be implemented. Clear procedures for packaging, labeling, and marking exact contents, loading and unloading hazardous cargo, including using appropriate equipment and following established safety protocols, should be established. Automation technologies such as robotics and sensors can be used to reduce the need for manual handling, and autonomous vehicles can be used to transport hazardous cargo, reducing the need for human intervention and minimizing the risk of accidents. A tracking and monitoring system using sensors and real-time tracking technologies should also be implemented to ensure that hazardous cargo is properly handled at every step of the way. Implementing a blockchain-based system can securely track the movement of hazardous cargo from origin to destination, ensuring that it is properly handled throughout the logistics process.

4.2. Fire protection and control system

Effective fire prevention and control systems are essential for seaports to ensure the safety of personnel, vessels, and cargo. To achieve this, seaports should install, maintain and audit appropriate fire suppression and detection systems throughout the port facility. Recent advancements in fire and chemical-resistant building materials should be used where possible, and adequate ventilation shall not be compromised to prevent the build-up of flammable gases. Seaports should implement a comprehensive hazard analysis program to identify and control potential sources of ignition. Regular fire drills and training must be conducted to ensure personnel are well-prepared to respond to an emergency. Advanced fire suppression technologies like firefighting systems that use additive-modified water mist, foam, or inert gases to suppress fires should be installed. Likewise, appropriate advanced fire extinguishing materials and technologies require to be maintained for every class of hazardous cargo handled at the port. Regular testing and maintenance of all fire suppression and detection systems should be conducted to ensure they are functioning properly. Advanced analytics and predictive modeling tools should be used to identify potential fire risks and optimize fire prevention strategies. An early warning system that uses advanced sensors and machine learning algorithms to detect potential fire hazards before they become serious should be implemented. Drones equipped with thermal cameras should also be used to quickly detect and respond to fires, improving response times and reducing the risk of damage. As in case of the Tianjin port accident, access to the fire source was restricted which resulted in the calamity that the world saw. Seaports should establish a system for sharing information and best practices related to fire prevention and response with other seaports and industry partners.

4.3. Corrosion control

Seaports should prioritize the implementation of effective corrosion control measures to protect their infrastructure from the harmful effects of hazardous cargo. These measures should include detailed and effective investigations, robust diagnosis systems, and the finalization of reliable and comprehensive countermeasures. The use of innovative structural health monitoring approaches and advanced chemicals monitoring sensors in surrounding air, and port waters on a regular basis and specifically after the incidence of any spills and leaks is highly recommended. Likewise, the use of cutting-edge technologies should be adopted for monitoring and preventing concrete strength, cracks, and their width and depth, cavities, spalling, and spalling from internal cavities. The same should be adopted for electric corrosion prevention, cathodic protection, galvanic anodes, protective coating systems, condition and rate of the corroded steel members and bars along the corrosive environment, chloride-induced corrosion and carbonation, and the alkali-silica reactivity. The authors recommend the usage and implementation of advanced broad-spectrum corrosion detection and characterization techniques in concurrence with the physical, environmental, and chemical situation at hand like direct physical measurement techniques (such as electromagnetic, acoustic, ultrasonic, fiber optic, radiographic and image processing techniques), direct electrochemical measurement techniques (such as linear polarization, electrochemical impedance spectroscopy, electrochemical noise, scanning Kelvin probe, coupled multi-electrode array sensor, and scanning electrochemical microscopy), and indirect measurement techniques (such as hydrogen probes, hydrogen monitoring, and brio-probes monitoring). It is also suggested to use advanced materials like nanocoating that are highly effective at preventing corrosion and can be applied to existing infrastructure. Finally, the use of drones equipped with advanced sensors and cameras to inspect hard-to-reach areas of infrastructure can reduce the need for human intervention and improve inspection accuracy.

4.4. Risk assessment and management measures

To ensure safety in seaports, regular risk assessments should be conducted, and appropriate risk management measures implemented as an integral part of the overall port logistics. This includes developing emergency response plans, training personnel, and establishing a system for reporting and investigating incidents. Advanced analytics, machine learning algorithms, and data visualization tools can be used to optimize risk management strategies. Key performance indicators can be utilized to track the effectiveness of risk management activities, and a continuous improvement program implemented to address areas for improvement. To ensure safe handling and transport of hazardous cargo, seaports should collaborate with all stakeholders, including shippers, carriers, and regulatory agencies. A cross-functional team should be established to coordinate all activities related to hazardous cargo handling and transport, fostering a culture of collaboration and shared responsibility among stakeholders. Clear communication channels should be established to ensure that safety measures are implemented and followed, and feedback mechanisms developed to facilitate continuous improvement and ensure stakeholders are aware of incidents and near-misses. To enhance collaboration and communication among stakeholders, seaports should use data analytics and information-sharing technologies, establish a collaborative framework, and develop joint initiatives and partnerships with other seaports and industry partners. Seaports should engage with stakeholders through various means to gather feedback on safety and security issues. Crowdsourcing and gamification techniques can be used to identify potential risks, improve opportunities, and promote safe behaviors. Seaports should also ensure compliance with regulations and standards and encourage the use of appropriate transport modes and packaging to minimize the risk of incidents.

5. Conclusion

Seaports are crucial for transporting hazardous cargo vital to global supply chains, industries, and the economy at large. However, operations involving hazardous cargo pose significant risks to port infrastructure, potentially leading to extensive damage or destruction. Such incidents can disrupt port logistics for extended periods, with recovery times extending over decades. Despite the critical nature of this issue, research on risk assessment specific to hazardous cargo and seaport infrastructure remains limited. This study addresses this gap by focusing on the comprehensive assessment of risks posed by hazardous cargo operations at seaports. This study builds on past literature, experts' opinions and past detailed accident reports to select the potential risk factors and build the causal relationship between them. Due to the lack of extensive data, the study employs expert opinions and logistic regression to construct and analyze a BN model, leading to several key conclusions:

- The study conducts predictive analysis and reports that the probability of infrastructure damage risk under standard operating conditions is below 5 %, which is unacceptable given the sheer volumes of hazardous cargo operations, and associated accident causation chains, and concomitant calamitous consequences. The primary risk factors identified are fire and explosion incidents initiated by hazardous cargo, cargo-induced corrosion, and inadequate cargo handling having probabilities of 8.73 %, 5.88 %, and 5.61 % respectively.
- The study also conducts diagnostic analysis and the evidence indicates that inadequate handling and corrosion contribute to increased risk by 153 % and 96 %, respectively, with fire and explosion risks also remaining significant, though its percent increase is 62.2 %, however, it has a probability of 14.16 % which is the second highest.
- The highest increment in the incidence probability of infrastructure risk is brought about by inadequate handling, which when evidence is set, increases the infrastructure risk probability from 4.26 % to 10.79 %.
- Through sensitivity analysis, the study identifies Inadequate Handling, Fire and Explosion, and Corrosion as the most critical risk factors and proposes practical measures to reduce the likelihood of infrastructure risks and mitigate damage severity.

This research aims to enhance understanding of the factors contributing to infrastructure risks during hazardous cargo operations, facilitating the development of effective risk mitigation strategies. It underscores the necessity for robust risk assessment models to prevent and manage potential damage, ensuring safer and more efficient port operations. Nevertheless, the study acknowledges limitations, such as the scope of considered factors, which could be expanded in future research to include risk categorization and damage level classifications using multi-state BN nodes. Further integration of real-time data on infrastructure damage from hazardous cargo operations could also improve the model's accuracy. Likewise, based on extensive past accident data, expert judgments, and chemical analysis, the hazardous cargo can be analyzed based on category and associated risk. In this domain, each type of hazardous cargo can be associated with a concomitant risk level by identifying the frequency of accidents, and the type and severity of consequences. Moreover, specific recommendations and policy guidelines could be proposed subject to each material, frequency, severity, and risk category. This study represents a foundational step towards understanding and mitigating risks associated with hazardous cargo operations at seaports.

CRediT authorship contribution statement

Rafi Ullah Khan: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jingbo Yin:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Elshan Ahani:** Writing – original draft. **R. Nawaz:** Investigation, Writing – review & editing. **Ming Yang:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgment

The authors (Rafi Ullah Khan, and Jingbo Yin) were supported by the National Natural Science Foundation of China [Grant No. 52472362], Ministry of Industry and Information Technology for research on the key technology of the high-tech ocean passenger ship construction logistics collection system [MC-202009-Z03], and the Open Research Fund of State Key Laboratory of Maritime Technology and Safety [Grant No. W24CG000037].

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